Mars Relay Description for Scout Proposals
April 24, 2006

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Introduction

This guide provides information on telecommunications relay services available for use by Scout missions to Mars beginning in 2011, based on relay capabilities of the 2001 Mars Odyssey (Odyssey) and the 2005 Mars Reconnaissance Orbiter (MRO). In cases where this guide conflicts with the AO, the AO takes precedence.

This guide outlines the orbital, communications and radiometric characteristics of each orbiting relay as needed to predict relay performance. It also presents guidelines on how to design Mars Scout missions that will employ orbiting relays at Mars.

Recognizing the value of relay communications for enabling and enhancing Mars exploration, the Mars Exploration Program has established a strategy of including relay communications capabilities on each Mars science orbiter. In the time frame of a 2011 Scout mission, the program intends to operate Odyssey and MRO as dual Mars relay assets. Though their coverage and capabilities are not identical, both of these orbiters support command and telemetry services, both conform to the CCSDS Proximity-1 Space Link Protocol, and both have sufficient propellant reserves to sustain operation through 2015 or later. By maintaining both Odyssey and MRO in this time frame, the Program has high confidence that relay services will be available to support any Scout mission concept that requires them. Scout proposers are free to leverage this infrastructure to enable or enhance their mission concept, consistent with the capabilities and constraints described in this document.

Guidelines

Relay Link Design

Relay link designers should carefully and clearly enumerate all link parameters associated with their side of the communications link and include sufficient margin to ensure reliable link performance. Proposals should include link budgets and explain the margin strategy used.

Critical Event Coverage

Critical event coverage can be provided by Mars infrastructure relay orbiter(s) provided the coverage meets the guidelines referenced in this guide. Mars Scout proposers can also use DSN assets (including the 70-m network) for providing critical event coverage. Proposers are also free to propose a combination of relay orbiter(s) and DSN coverage.

Orbiter Redundancy

Relay users should be able to support their primary mission using either MRO or Odyssey, in order to provide a redundant relay capability. Proposers may describe how their mission would be enhanced in the event that both orbiters are available.

Relay Cost

There is no direct cost to Mars Scout missions for using Mars infrastructure relay orbiter(s). However, Scout missions must pay for the amount of DSN tracking of Mars infrastructure relay orbiters needed to relay Scout telemetry and command data. Tracking costs are given in "NASA Mission Operations and Communications Services" in the Mars Scout library. Proposers should also budget for an appropriate level of project staffing required to interface with the relay orbiter missions for Mars relay planning and coordination efforts.

Relay Tests

Each relay orbiter will have a ground-based system for conducting compatibility tests with user relay radios. Testing is required at two levels: (1) radio compatibility and (2) end-to-end relay compatibility, including flight and ground system interfaces. Each Scout mission using relay services must include relay compatibility testing in its schedule and pay for its part of the tests.

Much of the remainder of this guide provides information about MRO and Odyssey orbits, services, radios, and antenna patterns to help proposers meet these guidelines.

The guide also gives information about the Earth link capabilities of the orbiters. At the end are sections on the use of orbiters by the Mars Exploration Rovers and some lessons learned from that mission.

Orbital Elements and Coverage

Table 1 shows the orbit elements and related data for MRO and Odyssey.

Table 1 Orbit elements for Odyssey and MRO

Orbit Element	MRO	ODYSSEY
Periapsis Radius (km)	3624.4	3766.1
Apoapsis Radius (km)	3691.1	3839.5
Semi-major Axis (km)	3657.7	3802.8
Eccentricity	0.0091	0.0096
Inclination (deg)	92.6	93.1
Ascending Node (deg)	-14.7	-159.8
Perigee Argument (deg)	-78.8	-83.7
Time from Perigee (sec)	-1818.8	-1423.8
Epoch	2008-147T01:00:00	2008-147T01:00:00
Related data	**MRO**	**ODYSSEY**
Periapsis altitude / location	255 km / South pole	370 km / South pole
Apoapsis altitude / location	320 km /North pole	444 km / North pole
Mean Local Solar Time (LST), ascending node	3:00 pm	5:00 am
Mean LST, descending node	3:00 am	5:00 pm
Orbit period	1 hr 52 min	1 hr 58 min

The MRO and Odyssey orbits are Sun synchronous, inclinations of 92.6 deg and 93.1 deg, respectively. Every time the orbiter crosses from south to north over Mars' equator, the local time at the ground directly below is 3:00 pm (MRO) or 5:00 am (Odyssey), local mean solar time.

The MRO and Odyssey orbit eccentricities and arguments of periapsis result in a frozen orbit. The term frozen orbit means the periapsis location remains nearly stationary over a fixed location, in this case, the south pole of Mars. With the periapsis location so fixed, a 65-70 km range between the periapsis and apoapsis altitudes results naturally due to the specific shape of the Martian gravity field.

Solar conjunctions of Mars occur in October 2006, December 2008, and periodically every 26 months after that. Solar conjunction does not affect surface communications with orbiters directly. As quantified in the "Solar Conjunction" section, it defines periods of time when uplinks and downlinks between the DSN and the orbiters are not possible.

Geometric pass durations and gaps vs latitude

Figures 1-3 (MRO) and 4-6 (Odyssey) are based on the orbit elements in Table 1. They define geometric conditions between each of the orbiters and surface vehicles as a function of the Mars latitude of the surface vehicle. They are based on composite statistics averaged over longitude and reflecting the maximum, average, or minimum over a 24-Sol simulation.

MRO

For the MRO orbit, Figure 1 shows the maximum (top curve), average (middle curve), and minimum (bottom curve) number of contacts (lasting at least one minute above 10 degrees) as a function of latitude of the surface vehicle.

Figure 2 shows the maximum (top) and average (bottom) potential MRO pass durations in minutes as a function of landed latitude, assuming a 10 deg minimum elevation angle from the surface. Pass duration is the time the orbiter appears above the minimum elevation angle.[1]

Figure 3 shows the maximum gap times between potential contacts with MRO. A gap is the duration of time between geometric contact opportunities. In polar locations, for the 1 hour 52 min MRO orbit, the gaps would be about 1-3/4 hours. At some near-equatorial latitudes, there is one contact per sol, resulting in a gap longer than 24 hours.

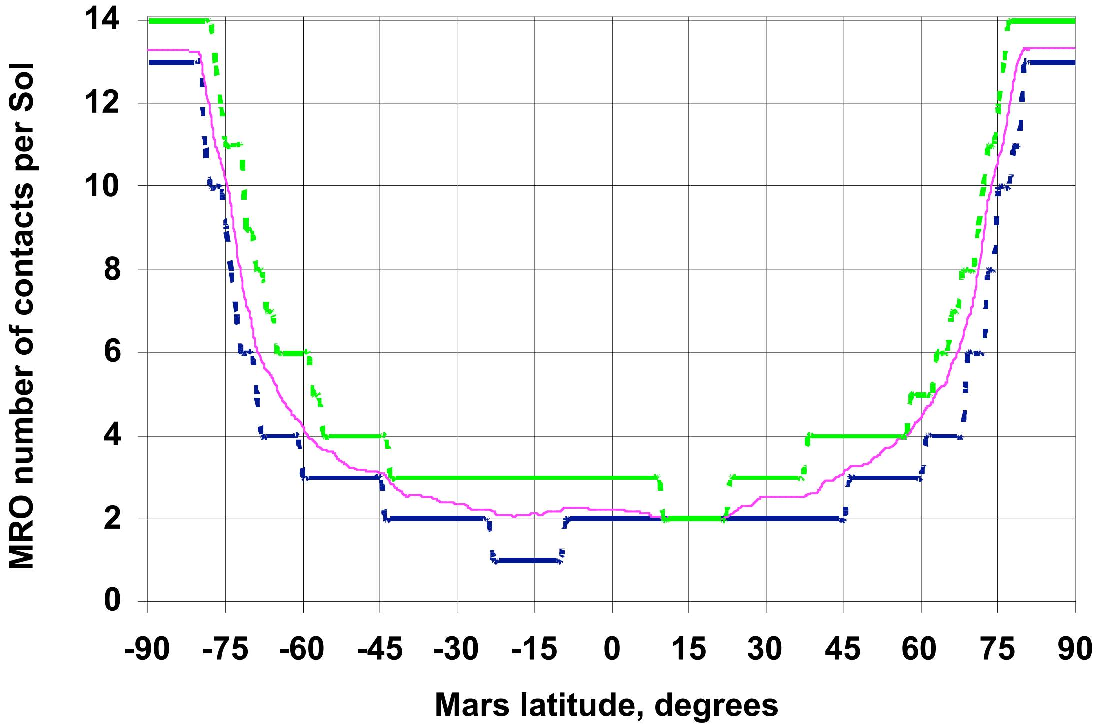

Figure 1 Max, average, min number of contacts per Sol vs latitude of lander for MRO orbit

[1] The minimum 10 deg elevation angle and assumed minimum 1-minute pass duration are for illustration. The figure omits minimum pass duration, which is generally not a useful statistic. For a near-circular sun-synchronous orbit, there will always be a pass geometry that results in near zero pass time except for surface locations near the poles.

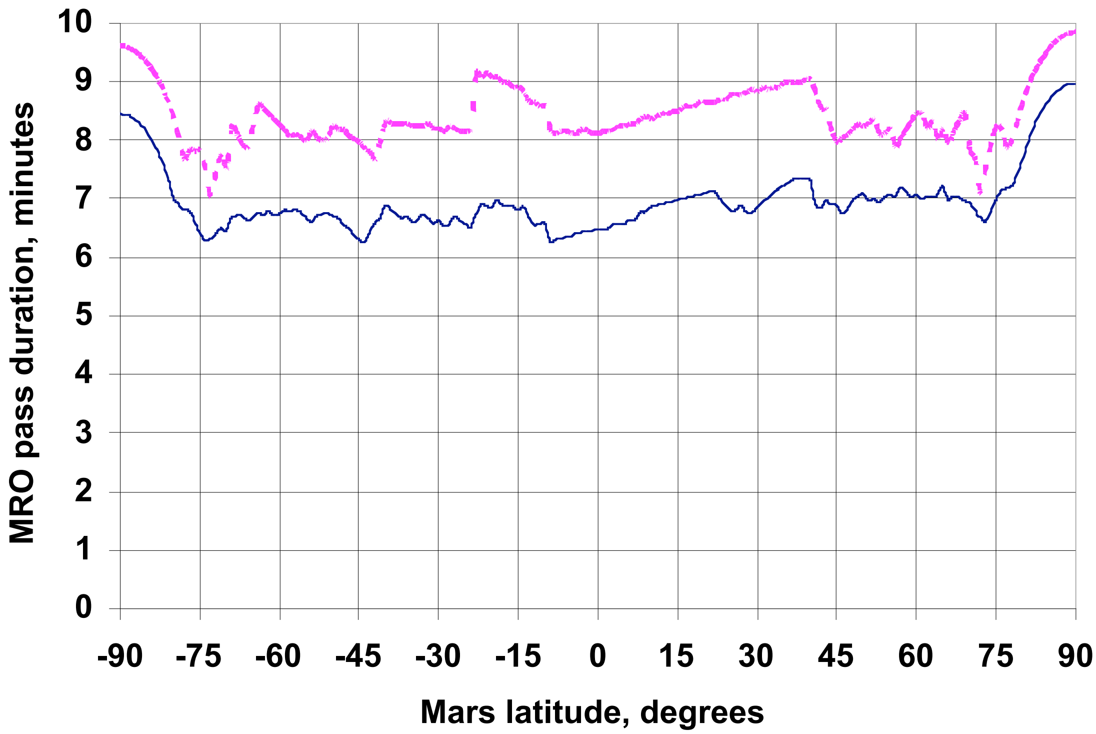

Figure 2 Max (top) and average (bottom) pass duration versus Mars latitude for MRO orbit

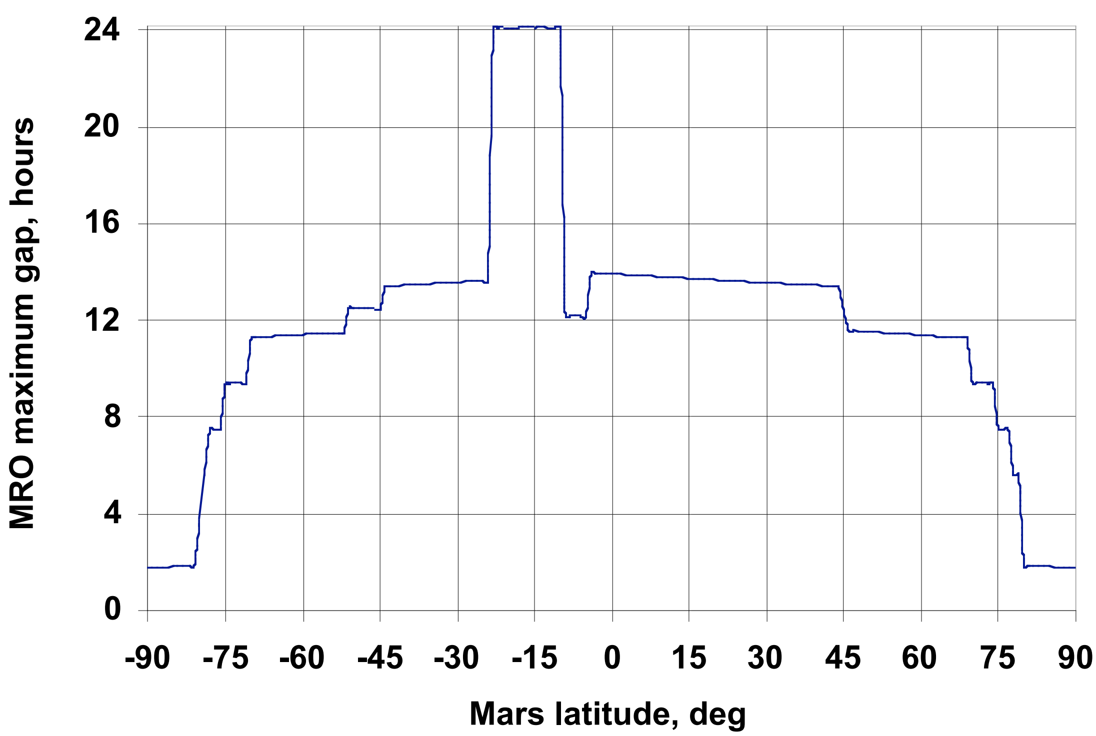

Figure 3 Maximum gap between potential MRO contacts vs Mars latitude

Odyssey

Figures 4, 5, and 6 provide data for the Odyssey orbit for a surface vehicle as a function of its latitude on Mars, comparable to Figures 1, 2, and 3 for MRO.

Figure 4 shows the minimum, average, and maximum number of contacts.

Figure 5 shows the average and maximum duration of longest contact.

Figure 6 shows the maximum duration of the gap from the end of one contact to the next.

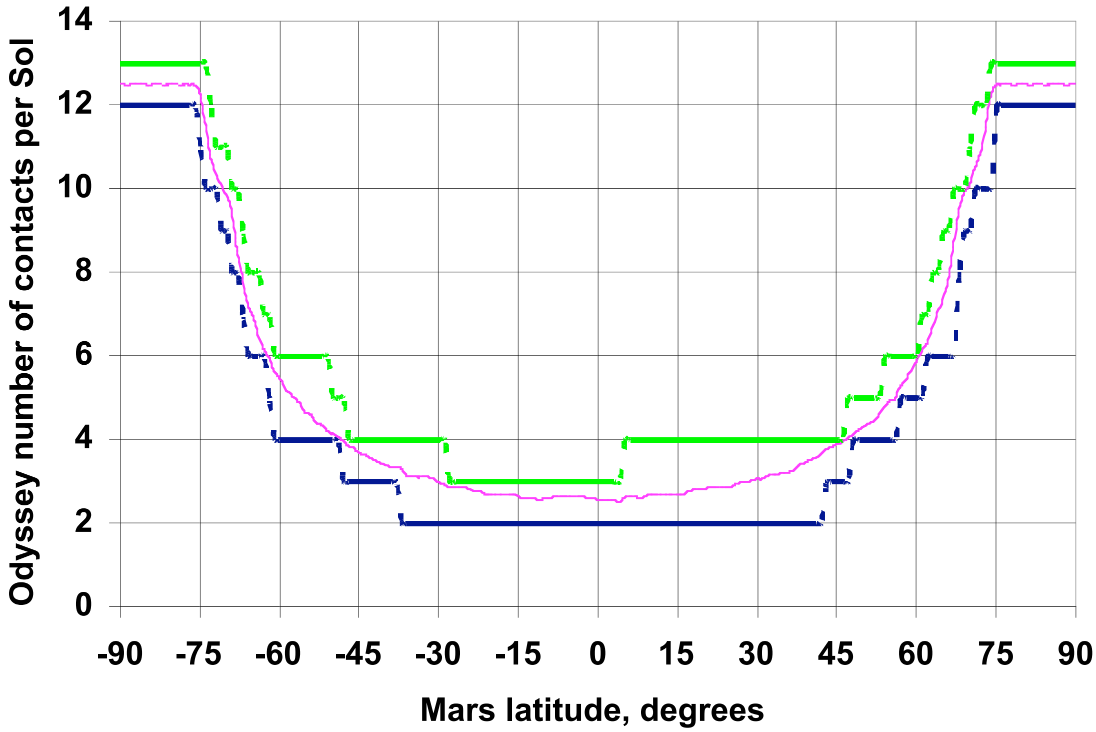

Figure 4 Max, average, min number of contacts per Sol vs latitude of lander with Odyssey orbit

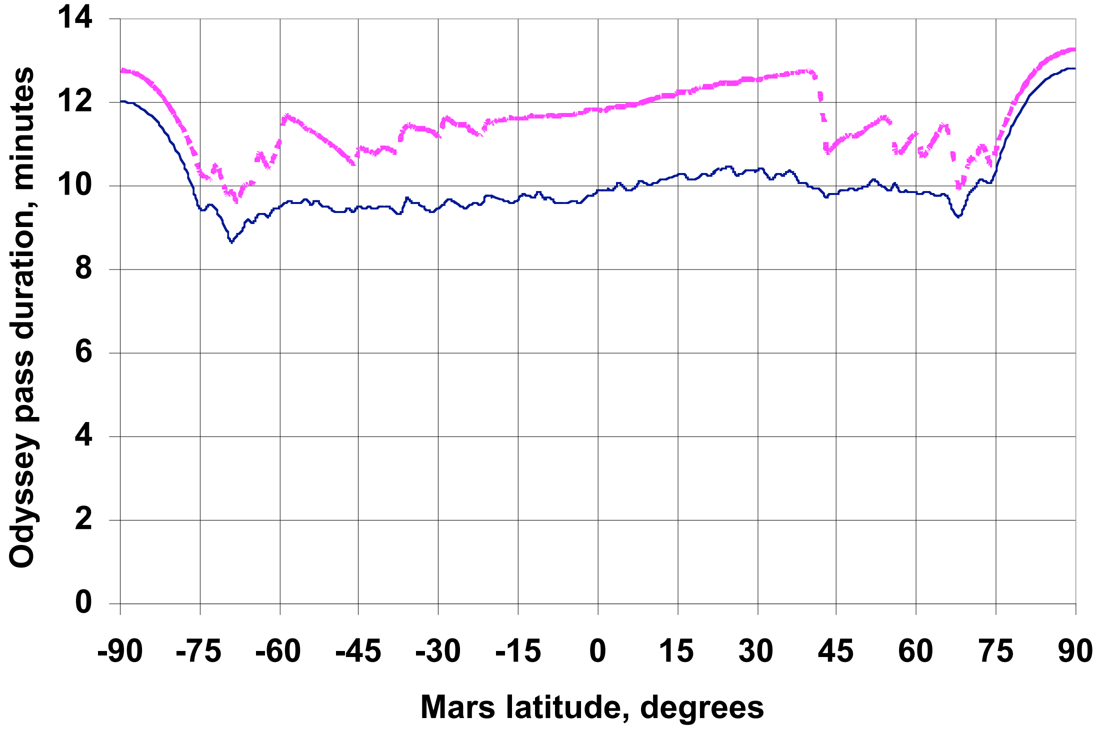

Figure 5 Max (top), average (bottom) pass duration per Sol vs Mars Latitude for Odyssey orbit

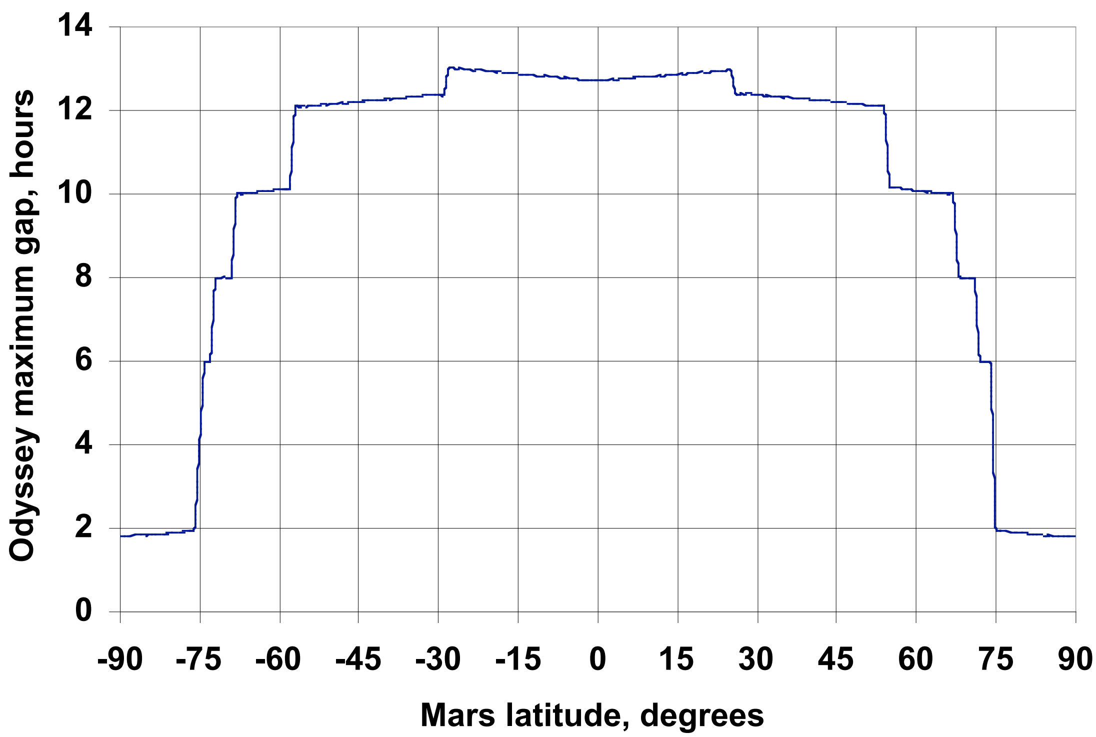

Figure 6 Maximum gap between potential Odyssey contacts vs Mars latitude

Supported Services

The relays on both MRO (Electra radio) and Odyssey (CE-505 radio) are compatible with the CCSDS Proximity-1 Space Link Protocol [Ref. 1 and Ref. 2].

Prox-1 transfer frames are sent on both the forward link (from the orbiter to the surface vehicle) and on the return link (surface back to the orbiter) using the Prox-1 protocol link management in either reliable (retransmission) or expedited (no retransmission) mode. In retransmission mode, an ARQ protocol is utilized to request retransmission of any proximity frames that are not received error-free.

Both MRO and Odyssey also provide a relay service not utilizing the Prox-1 protocol. MRO calls this service Raw data, and Odyssey calls it Unreliable bit stream data. Both orbiters provide a form of Doppler data, and both provide a form of open loop data.

The MRO Electra radio has redundant ultra stable oscillators (USOs). MRO is currently operating on USO1 (S/N 74587). Odyssey has a sufficiently stable oscillator (SSO) that the UHF transceiver can reference. Table 2 gives the stabilities of the USOs and the SSO.

Table 2 Measured MRO USO and Odyssey SSO stabilities

MRO USO stability			Odyssey SSO stability	
USO-1 (S/N 74587	USO-2 (S/N 74585)	Period	SSO stability	Period
$1.04*10^{-12}$	$1.09*10^{-12}$	0.1 sec		
$0.44*10^{-12}$	$0.41*10^{-12}$	1 sec		
$0.51*10^{-12}$	$0.54*10^{-12}$	10 sec	$1.0*10^{-11}$	20 sec
$1.01*10^{-12}$	$0.75*10^{-12}$	100 sec	$1.0*10^{-11}$	5 min
$8.14*10^{-12}$	$1.26*10^{-12}$	1000 sec	$1.0*10^{-9}$	24 hr
			$1.0*10^{-8}$	7 days

MRO Services

In addition to the Prox-1 relay services defined below, the MRO Electra transceiver can provide radiometric services to support navigation activities such as:

- Surface asset position determination
- Orbit determination
- Tracking during critical events such as entry, descent, and landing (EDL)

Electra radio timing and radiometric services are compatible with the CCSDS Prox-1 recommendation. The MRO Electra radio provides one basic time service (time stamps) which can be used for event timing and reconstruction, clock correlation, and 1-way ranging.

Table 3 lists the MRO services, and indicates which ones can be provided simultaneously (that is, within a single relay session).

Table 3 MRO Available Data Services and Concurrency

MRO service	Service capabilities within one session		
Prox-1 data (reliable or expedited	X		
Prox-1 time stamp	X		
Raw data		X	
Phase-power (Doppler)	X	X	
Open loop record			X

Proximity-1 (MRO). Basic Prox-1 service is described in previous section.

Typically the MRO Electra will initiate a Prox-1 session by sending a string of "hail" data packets while looking for a response from the specific lander identified in the hail packet. This standard operating procedure can be reversed, that is, lander-initiated relay sessions are possible.

The hail includes information describing the session operating mode for both the forward and return link directions. This includes operating frequency, data rate, and channel coding mode, to name a few important things. The current software implementation on the MRO Electra allows for only a single data rate per Prox-1 session. Future software upgrades intended for support of the MSL mission will include the ability to dynamically sense link power and performance metrics and automatically negotiate a change in data rate to accommodate the change in channel capacity. Proposers may assume that this capability is present at the time of the Scout mission.

In Prox-1 reliable mode, data frames with bit errors are automatically detected and retransmitted via a standard Go-Back-N protocol scheme.

In Prox-1 expedited mode, data frames with bit errors are discarded on the receive end. All that remains is a record of the data frame number missing from the frame sequence accounting.

The MRO Electra radio has a number of commandable timer settings that allow it to flywheel over short link drop outs or that force automatic link reacquisition after longer signal drop out periods. These functions are built into the MRO Electra Prox-1 session management to maximize data return in a relay link environment with variable link performance.

Prox-1 sessions are terminated by timed sequenced command or by the time out of a dropped signal count down timer.

Time Stamp packets (MRO). Time stamp data consists of snapshots of the local Electra clock corresponding to the ingress or egress times of Prox-1 Frame sync markers. Thus time stamp data may only be collected in conjunction with Prox-1 mode operations. The time stamps are paired with the corresponding Prox-1 frame sequence numbers and noted as arriving or departing frames. These can be processed on the ground in conjunction with similar remote asset Prox-1 time stamp data to achieve user-to-MRO Electra clock correlation.

Electra can time tag the trailing edge of the last bit of the attached frame sync marker of any incoming or outgoing Prox-1 transfer frame to an accuracy of 60 nanoseconds RMS relative to the Electra clock.

Raw data (MRO). In Raw data mode there is no hailing or link establishment protocol, nor is there any session data management or accounting protocol. A link is established by time sequence transmissions and reception at both ends of the link. For example, the MRO orbiter is sequenced to begin listening for a signal at time X and another vehicle is sequenced to begin sending at time X+delta.

In addition to coordinated sequence timing, both sides of the link must agree beforehand to the same data link mode settings, for example frequencies, data rates and coding.

While the raw data sent from the surface may have its own internal format, Electra and MRO know nothing of these native data structures and treat the received data as a continuous bit stream that is subsequently partitioned into 32-byte boundary data units that are passed to the ground.

Phase & Power data (MRO). MRO's Electra transceiver can sample and record phase signal power of a phase locked received carrier signal. This radiometric information is highly accurate on two accounts. First, the phase information is relative to the phase of the Electra USO signal with stability of better than 1 part in 10^{-12}. Second, the capture of successive samples is tied directly to the USO based local clock to achieve a highly stable inter-sample time period. In effect, this data forms the basis for a Doppler metric. Each sample contains phase, AGC power, I amplitude, Q amplitude, and a USO based time tag.

The Electra radio has a minimum accumulated Doppler phase measurement interval of 1 second, with the capability to command the output rate to integer multiples of the minimum (5, 10, 20, 60 sec, etc.) The Electra can time tag the accumulated Doppler phase measurement with a minimum accuracy of 60 nanoseconds relative to the MRO spacecraft clock.

Open Loop Data (MRO). Open loop data consists of high rate in-phase and quadrature (I & Q) samples of the digital representation of the down-converted signal given a fixed receive center frequency and no closed loop signal tracking. It is required of the user to specify a data collection rate, data collection filter bandwidth and data collection center frequency that will achieve the capture of the intended received signal bandwidth. The user is also required to specify the fixed receiver gain setting that effectively defines the peak-to-peak signal amplitude range into MRO. Electra provides 8 bits/sample for the I channel and the Q channel, corresponding to signal level range of 51 dB.

Sample collection timing is based on a highly stable USO synchronous internal clock. Available sampling rates range in powers of 2 from about 1.15 Hz to about 150 kHz. Data may be collected with or without time tags.

Odyssey Services

Table 4 summarizes the Odyssey services, and which ones can be provided simultaneously (that is, within a single relay session).

Table 4 Odyssey Available Data Services and Concurrency

Odyssey service	Service capabilities within one session		
Prox-1 data (Reliable or expedited)	X		
Unreliable bit stream (Raw Data Mode)		X	
Doppler	X	X	
Open Loop Record (Canister Mode)			X

Proximity-1 data (Odyssey). Odyssey Prox-1 services are an operational subset of those described in the MRO services section. There are several differences in the service names that Odyssey uses and there are constraints on the Odyssey Prox-1 settings.

Under the Odyssey project, the "Reliable (Retransmission) mode is called Reliable Bit Stream or Sequence Controlled mode. The Expedited mode is called Message-Bypass mode.

For Odyssey Prox-1 operations, the Prox-1 data packet size is not directly user selectable but is a fixed function of the combination user specified Rx and Tx data rates. For the Reliable mode, the Odyssey Go-Back-N value is fixed to a value of 2 frames. These Odyssey CE-505 radio fixed settings are "tuned" for efficient link operation with a second CE-505 lander radio. The Electra radio data frame size and Go-Back-N values can be user set to accommodate efficient operations with a CE-505 radio. Thus an MRO Electra can be Prox-1 tuned to efficiently interoperate with a CE-505 equipped lander and an Electra equipped lander can be Prox-1 tuned to efficiently interoperate with a the CE-505 based Odyssey orbiter.

Unrealiable bit stream mode (Odyssey). This mode is equivalent to the MRO "Raw Data" mode. In this mode, the frame layer protocol is not used. The Odyssey transmit buffer needs to have data ready to send, otherwise the transmitter is shutdown and the link dropped.

Doppler data (Odyssey). The difference between a phase locked carrier and a reference frequency can be measured and recorded by the Odyssey CE-505 radio Doppler function. The reference frequency can be derived from the oscillator internal to the transceiver or from the Odyssey sufficiently stable oscillator (SSO),

Doppler measurements are put in fixed length packets containing the strobe-enabled time (seconds and subseconds), the zero-cross counter and the time counter.

Canister mode (Odyssey). This mode is equivalent to the MRO "Open Loop Record" mode. In Canister mode, the Odyssey CE-505 radio samples the incoming baseband signal at a rate of 83.6 kHz and with a 1-bit analog-to-digital (A/D) conversion. The center frequency of the open loop record is always at the nominal 401.6 MHz receive center frequency. No other sample rates or A/D conversion bit widths are possible. Due to Odyssey flight software constraints, the precision of the time-stamp is 20 ms.

The Canister mode data is put in fixed length packets, like the Doppler data packets, but with the raw RF data replacing the Doppler counter data.

MRO Operating Modes

Figure 7 is a block diagram of an Electra UHF transceiver. The EUTs and USOs are redundant. The diagram shows the restrictions on allowable combinations of use with the MRO command and data handling (C&DH) subsystem and solid state recorder (SSR).

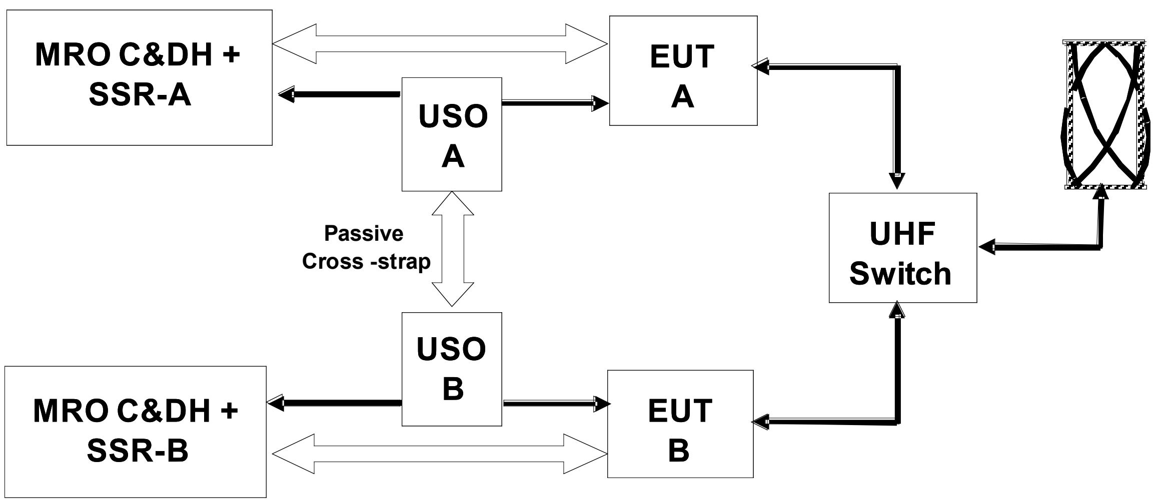

Figure 7 MRO/Electra UHF subsystem block diagram and interfaces with C&DH and SSR

Table 5 defines the major operating modes, functions, and constraints for MRO Electra.

Table 5 MRO Electra Modes, Functions and Performance

Capability	Values
Protocol	Prox-1 (Reliable and Expedited Link Layer protocols)
Frequencies	See next section (including Table 8)
Modes of Operation	Half duplex[2] Rx and Tx (no Prox-1 protocol in half duplex) Full duplex transceiver
Full duplex carrier modes	Coherent, noncoherent
Transceiver RF output power	5.0 W full duplex, 7.0 W half duplex
Transceiver to antenna circuit loss	-0.42 dB
Antenna gain	Figure 9 (437.1 MHz) and Figure 10 (401.6 MHz)
Carrier modulation modes	Suppressed carrier, residual carrier (60 deg mod index)
Modulation types	Residual carrier BPSK with bi-phase-L (Manchester) Suppressed carrier BPSK
Frequency reference	Ultra stable oscillator
Rx and Tx symbol rates	1, 2, 4, 8, 16, 32, 64, 128, 256, 512, 1024, 2048 ksps. Also, adaptive data rate mode
Received signal power range	-140 to -70 dBm
Encoding	Uncoded, (k=7, r= 1/2) convolutional, differential symbol coding
Decoding	Uncoded, (k=7, r= 1/2) convolutional (3 bit soft decode)
Scrambling / Descrambling	V.38
Acquisition and tracking loop	Second-order PLL, with loop bandwidth 10 Hz to 10 kHz (for received signal from -140 dBm to -70 dBm)
Tracking range and rate	+/- 20 kHz, +/- 200 Hz/sec

Table 6 and Table 7 define the MRO signal level thresholds for convolutionally coded data and uncoded data, respectively. The threshold values in both tables assume the following MRO mode and link conditions.

- BPSK, full duplex: 0 dB margin, mod index 60 degrees. The tables assume residual carrier mode operation. At the higher data rates, suppressed carrier modulation may be considered for more power-efficient operation.
- Nominal filter losses and noise figure, Mars noise temperature 210 K.
- Threshold power (dBm) is defined at the input to the antenna connector at 401.6 MHz.

Add link margin per your design requirements.

[2] The term "full duplex" is used by MRO in the conventional sense of simultaneous forward and return link capability at separate frequencies. The term "half duplex" means that Electra's transmitter and receiver are not on simultaneously even though the forward and return links may be on separate frequencies.

Table 6 MRO coded receive signal configuration and threshold data

Bit rate, kbps (coded)	Threshold Power, dBm (at Antenna Connector)
1	-130.8
2	-127.8
4	-124.8
8	-121.8
16	-118.8
32	-115.8
64	-112.8
128	-109.7
256	-106.7
512	-103.3
1024	-99.6
Performance is based on use of a 16,384 bit Prox-1 frame length. Code is k=7, r=1/2, 3-bit soft decision. Data rate = 0.5*symbol rate. BER = 4.53*10-7, Prox-1 FER = 1.0*10-3, Threshold Eb/No = 5.5 dB	

Table 7 MRO uncoded receive signal configuration and threshold data

Bit rate, kbps (uncoded)	Threshold Power, dBm (at Antenna Connector)
1	-126.0
2	-123.0
4	-119.9
8	-116.9
16	-113.9
32	-110.9
64	-107.9
128	-104.8
256	-101.7
512	-98.5
1024	-94.9
2048	-91.1
Performance is based on use of a 1,000 bit Prox-1 frame length. Uncoded data. Data rate = symbol rate. BER = 1.08*10-6, Prox-1 FER = 1.0*10-3, Threshold Eb/No = 10.5 dB.	

MRO Frequencies

MRO Electra implements frequency agility and swappable transmit and receive bands. While complying with Prox-1 channel definitions for eight frequency pairs, MRO Electra supports the 16 preset frequency pairs, defined in Table 8.

Table 8 Prox-1 "Blue Book" channel numbers and frequencies

Channel Number	CCSDS Forward Frequency (MHz)	MRO Preset Forward Frequency (MHz)	CCSDS Return Frequency (MHz)	MRO Preset Return Frequency (MHz)
0	437.1	437.1	401.585625	401.585625
1	435.6	435.6	404.4	404.4
2	439.2	439.2	397.5	397.5
3	444.6	444.6	393.9	393.9
4	435 to 450	436	390 to 405	401.4
5	435 to 450	438	390 to 405	402
6	435 to 450	440	390 to 405	402.6
7	435 to 450	441	390 to 405	403.2
8		442		391
9		442.5		392
10		443		393
11		445		395
12		446		395.5
13		447		396
14		448		399
15		449		400

In addition to these 16 preset pairs, the MRO Electra radio has the capability to tune its Tx and Rx frequency across the entire 390 MHz to 450 MHz band, thus any frequency pair combination within this band is possible. For half duplex operation, any pair of frequencies will work as an operational pair. For full duplex operation, the Tx frequency must be chosen in the range of 435 MHz to 450 MHz and the Rx frequency must be chosen in the range of 390 to 405 MHz.

Frequency Selection and Interference considerations

Odyssey (next section) operates on a fixed pair of forward and return frequencies. The term “forward link” is defined as a transmission from an orbiter to a relay user. “Return link” is a transmission from a relay user to an orbiter.

Interference between landers is possible if Odyssey can see more than one lander simultaneously. Such interference is mitigated through the multimission relay scheduling process and utilizing the capability of the Proximity-1 hailing procedure to address a specific user by spacecraft ID.

Odyssey Operating Modes

Figure 8 is a block diagram of the Odyssey UHF subsystem.

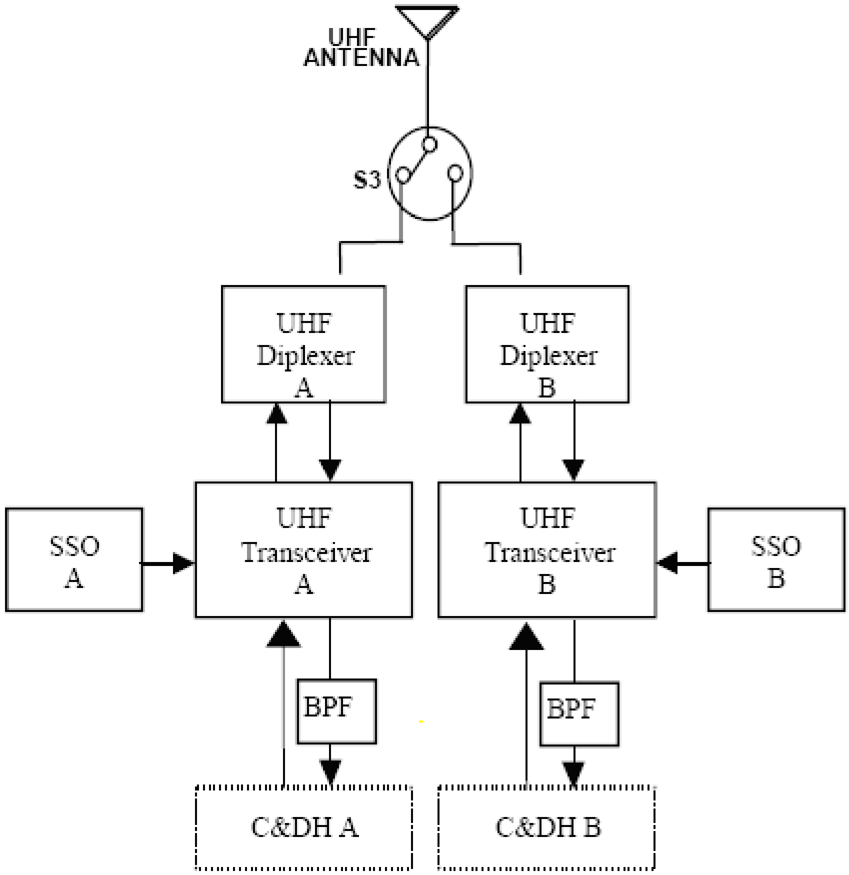

Figure 8 Block diagram of Odyssey UHF subsystem

The transceivers and the SSOs (sufficiently stable oscillators) are block redundant. However, there is no cross-strapping between the Odyssey CD&H and the transceivers and between the transceivers and the SSOs. A single antenna will provide transmitting and receiving capability and a switch will connect it to the active UHF radio.

Table 9 defines the major operating modes, functions and constraints for Odyssey.

Table 9 Odyssey UHF Modes, Functions and Performance

Capability	**Values**
Protocol	Prox-1
Carrier frequency	437.1 MHz forward 401.585625 MHz return
Frequency reference	Sufficiently stable oscillator (SSO), with Allen deviation better than $1*10^{-11}$ for integration times between 1 and 1000 sec.
RF output power	40.5 dBm (11.2 W) nominal

Capability	Values
Antenna gain	Figure 11 (437.1 MHz) Figure 12 (401.6 MHz)
Transceiver to antenna circuit loss	-1.0 dB at 437.1 MHz (forward) -1.8 dB at 401.6 MHz (return)
Receiver noise figure	2.5 dB
Carrier modulation modes	PCM / bi-phase-L (Manchester) / PM (60 deg mod index) FSK NRZ
Rx and Tx data rates	8, 32, 128, 256 kbps
Encoding	Uncoded, (k=7, r= 1/2) convolutional
Decoding	Uncoded, , (k=7, r= 1/2) convolutional (3 bit soft decode)
Acquisition and tracking	Acquires +/- 8 kHz off center frequency

Table 10 defines the Odyssey signal level thresholds for coded and uncoded data. The table assumes the use of transceiver SN001 (Odyssey Side A). Thresholds are at the antenna connector, same as for MRO.

Table 10 Odyssey coded and uncoded receive signal thresholds

Bit rate, kbps	Threshold Power at Antenna (dBm) (Coded data)	Threshold Power at Antenna (dBm) (Uncoded data)
8	-119.2	-116.8
32	-114.7	-110.8
128	-108.5	-104.8
256	-104.6	-101.6

- BER = $1*10^{-6}$
- Code is k=7, r=1/2, 3-bit soft decision.
- Symbol rate = 2*symbol rate for coded data.
- Mars noise temperature = 210 K at antenna.

A link with Odyssey is initiated by Odyssey sending a Prox-1 Hail at 8 kbps. The Hail includes “Set Transmit” and “Set Receive” directives that described the configuration of transceivers at both ends of the link. Information about the intended communications mode, data rates, coding, and modulation are all contained in this Prox-1 Hail data frame.

Orbiter antenna patterns

The MRO and Odyssey antennas are right circular polarized (RCP) for both forward and return link.

Figures 9 and 10 (MRO) and Figures 11 and 12 (Odyssey) show gain in dBi versus angle from boresight (cone or theta). In each figure, the solid curve is the average gain over cuts made in the orthogonal axis (clock or phi). The dotted curves above and below the solid curve are the gains for the best-case and worst-case clock cut, respectively.

MRO gain patterns

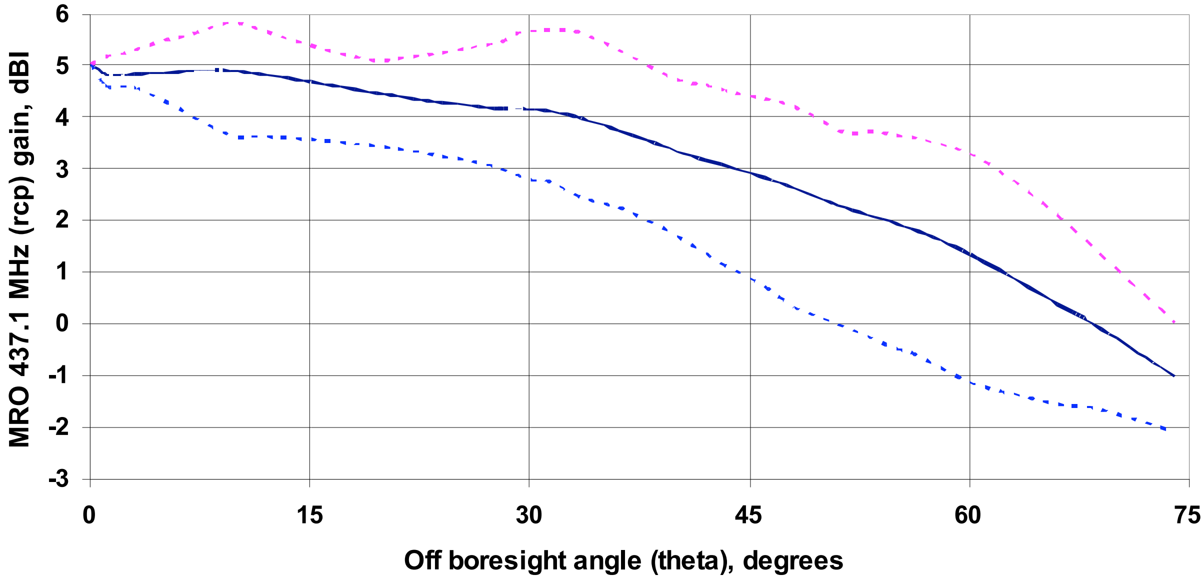

Figure 9 MRO 437.1 MHz (rcp) gain pattern

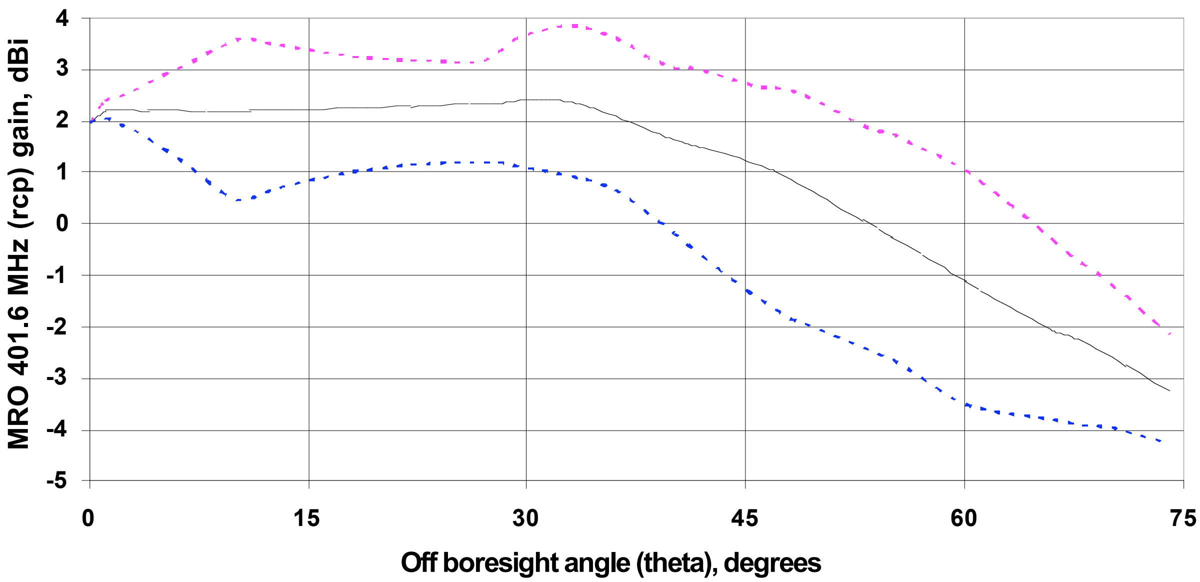

Figure 10 MRO 401.6 MHz (rcp) gain pattern

Odyssey gain patterns

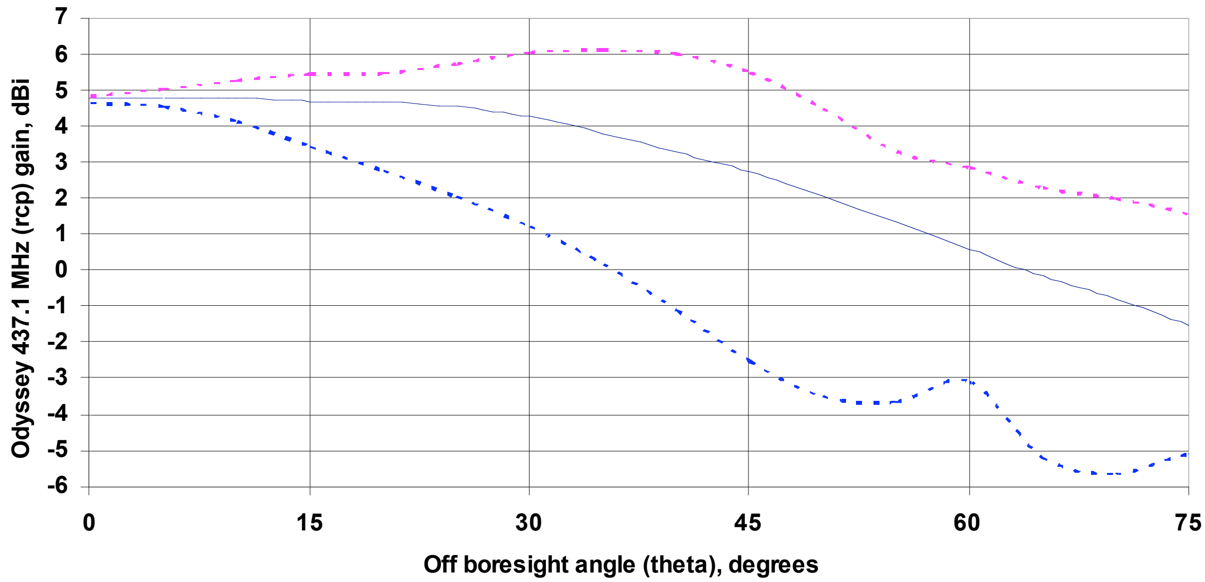

Figure 11 Odyssey 437.1 MHz (rcp) gain pattern

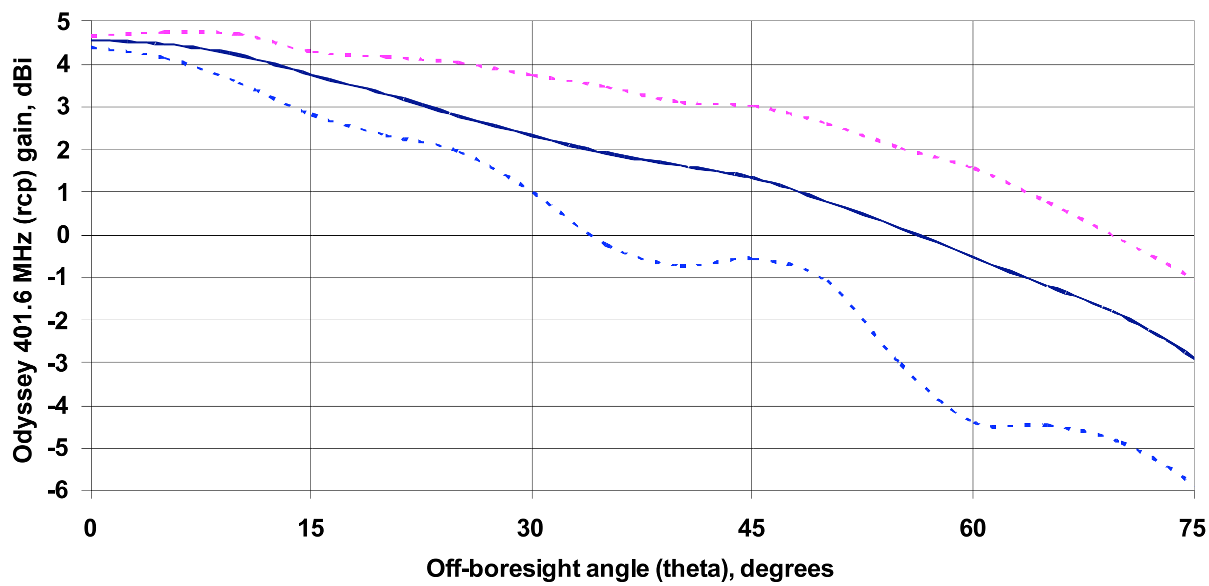

Figure 12 Odyssey 401 MHz (rcp) gain pattern

Orbiter UHF Antenna Geometry

MRO

The MRO Electra Payload provides a single nadir looking UHF LGA. The antenna shares the Nadir deck with science payloads. The portions of these nearby payloads that are responsive at UHF frequencies couple with the antenna and distort its nominal gain pattern. To compensate for this, the MRO mission plan allows for spacecraft roll steering of up to 30 degrees to point the better parts of the UHF antenna pattern toward the surface user. The orbiter sets up for this pass by roll steering to a fixed roll angle. The Electra payload performs the pass, and then the orbiter rolls back to the standard Nadir pointing position.

Odyssey

The Odyssey relay antenna is not articulated, nor will the spacecraft be steered prior to or during a relay pass.

The Odyssey spacecraft nadir deck is pitched 17 deg behind nadir, opposite the direction of flight. This is because Odyssey is canted relative to the velocity vector, as shown in Figure 13.

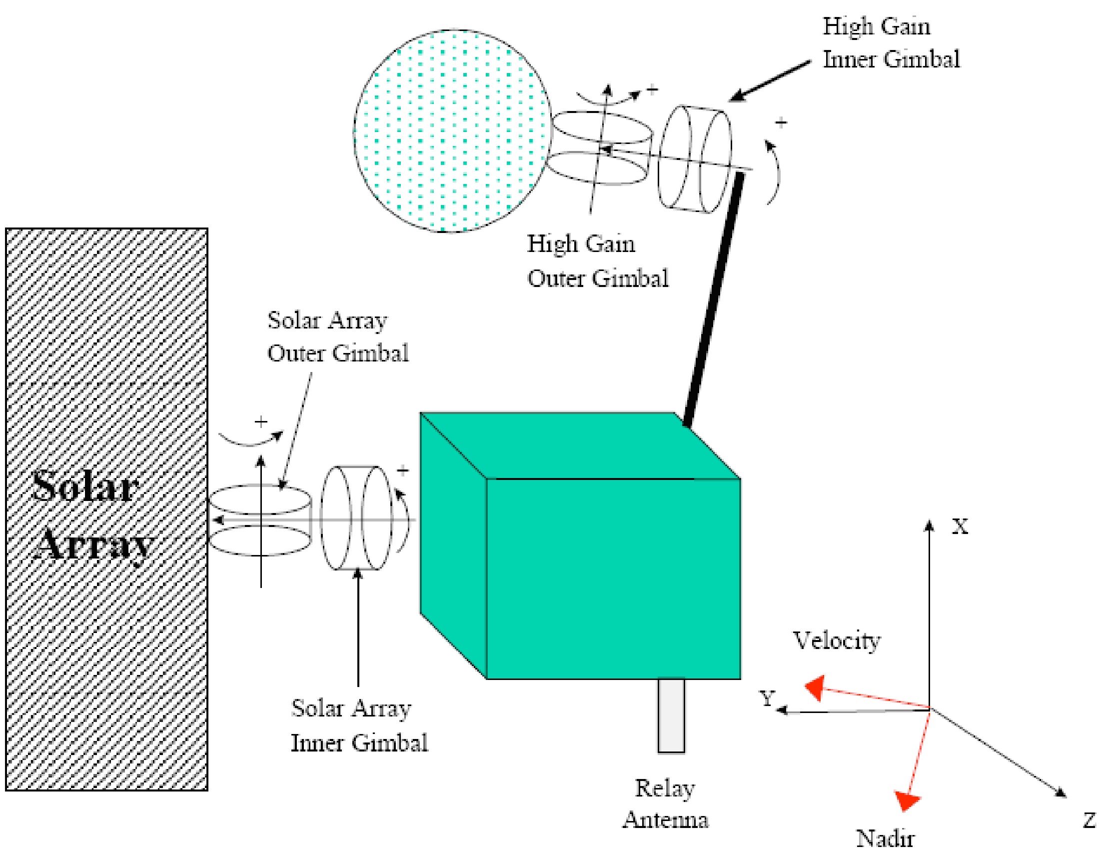

Figure 13 Odyssey and UHF antenna geometry

The cant angle, -17 deg for Odyssey, is the angle between the orbiter y-axis and the velocity vector. The UHF antenna boresight is along the –x axis. The antenna is pointed off nadir by the cant angle. This fixed offset between nadir and the antenna boresight must be taken into account when using the Odyssey antenna patterns (Figures 11 and 12) and when planning relay passes.

Link Margin Policy

Proposers should quantify their link margin assumptions and justify them based on the nature, complexity and scope of the telecommunications link design uncertainties as well as the criticality of the data transmitted.

Data Volume Coordination

Coordination of relay opportunities among surface assets, orbiters (including MRO's science activities) will be performed by the Multi-Mission Ground Systems and Services Program Office (MGSS), as shown in Figure 14.

Every four weeks, as part of the long range coordination process, each project (including the orbiters) will provide ephemeris predictions, as well as known non-relay periods, to MGSS as part of the coordination process. On a weekly basis, for near-term coordination planning, the projects will update this information and provide specific "requested" overflights. Relay opportunities will be assigned as part of the MGSS's short-range coordination process.

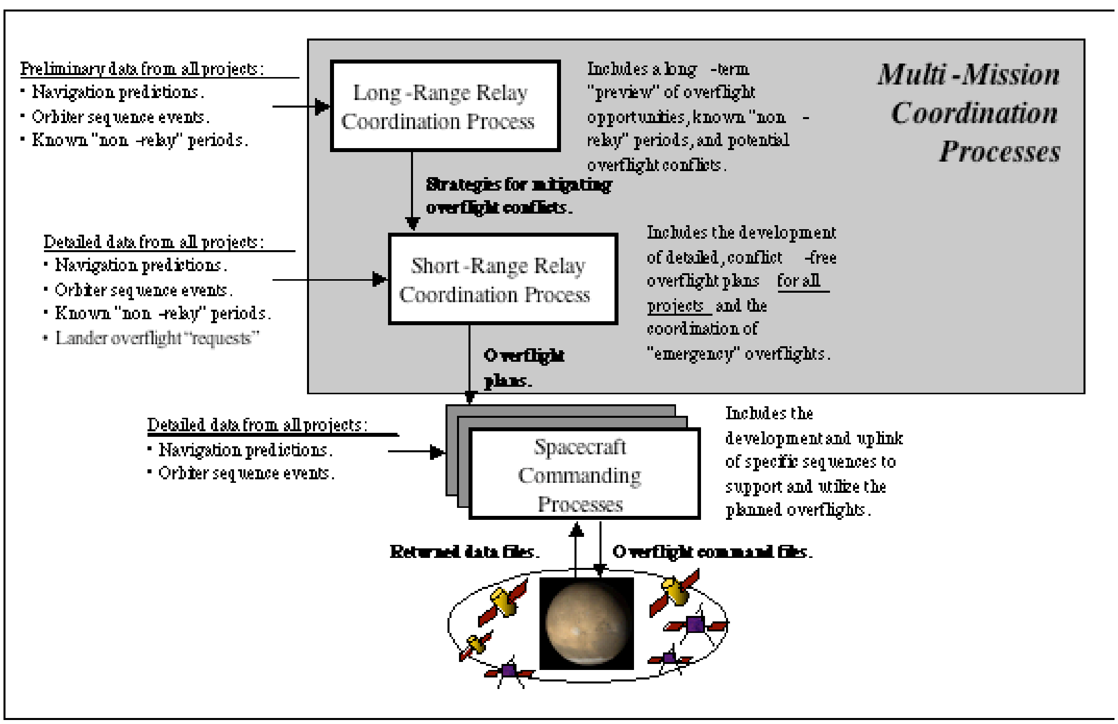

Figure 14 Multi mission Mars relay coordination process

Data volume constraints

MRO

The potential data-return volume is limited primarily by the limited relay contact time, which bounds the amount of data that can be sent from a user to MRO. The MRO ground data system is capable of handling 230 Gb of Orbiter data per day received from the spacecraft. During the prime science mission (through 2008), out of that total, 0.5 Gb per day is allocated for Electra return link data. During the relay phase (post 2008), a larger volume can be negotiated for relay data users. The allocation of data volume among MRO users would be part of the MGSS coordination process.

Odyssey

The potential data-return volume is constrained by the allotment of Odyssey onboard memory. The volume of data that may be relayed through Odyssey per pass is constrained by data that may remain in the Odyssey buffer from the previous relay pass. How quickly the buffer can be emptied is a function of the DSN coverage allocated to Odyssey for downlinking this data to Earth.

Prior to its surface operations a project will coordinate an update to the Odyssey UHF Relay Operations Plan. As an example, prior to MER surface operations in early 2004, Odyssey allocated a total of 12.5 MBytes (100 Mbits) of Odyssey onboard memory to both MER rovers (and to Beagle II, which did not operate). For the MER primary surface mission, the allocation was later increased to 120 Mbits per rover.

Orbiter to DSN Link

This section describes characteristics of the X-band links between the Deep Space Network and the orbiters that affect the forward and return link operations with surface vehicles. Mars Scout missions should assume the orbiters will obtain 34-m coverage (and therefore be limited to 34-m uplink and downlink bit rate capabilities) for standard operation. The 70-m network is available for critical events and emergency situations.

Solar conjunction

The MRO and Odyssey X-band downlink capabilities described in the next paragraphs do not apply during solar conjunction, when the Mars-Earth communications path is close to the sun. Proposers should assume that neither commandability from Earth nor data return to Earth will be possible when the Sun-Earth-Mars angle is less than 3 deg.

MRO

Uplink rates. For normal operations, the uplink rate is 2 kbps (the maximum possible with the SDST). Other SDST rates, down to 7.8125 bps, are available.

Downlink rates. Figure 15 shows the profiles of the X-band downlink Pt/No via the HGA for 34-m and 70-m stations through the MRO “relay” mission ending in 2010. Beyond that date, the Pt/No would generally repeat within the same limits.

MRO has a variety of coding schemes available to maximize the rate capability at a particular range. The coding options available are Reed-Solomon (R-S), R-S plus convolutional code (k=7, rate 1/2). The figure also shows the Pt/No thresholds at X-band[3] for six standard MRO downlink modes/rates. The 34-m profile shows that 500 kbps is supportable at all Earth-Mars ranges while 1.3 Mbps, 1.5 Mbps, and 2.61 Mbps are supportable for increasingly smaller ranges.

Downlink data rates at Mars are planned to range from 650 kbps to 2600 kbps while utilizing a 34m DSN station. For downlinks to a 70m station, data rates range from 1750 to 3500 kbps.

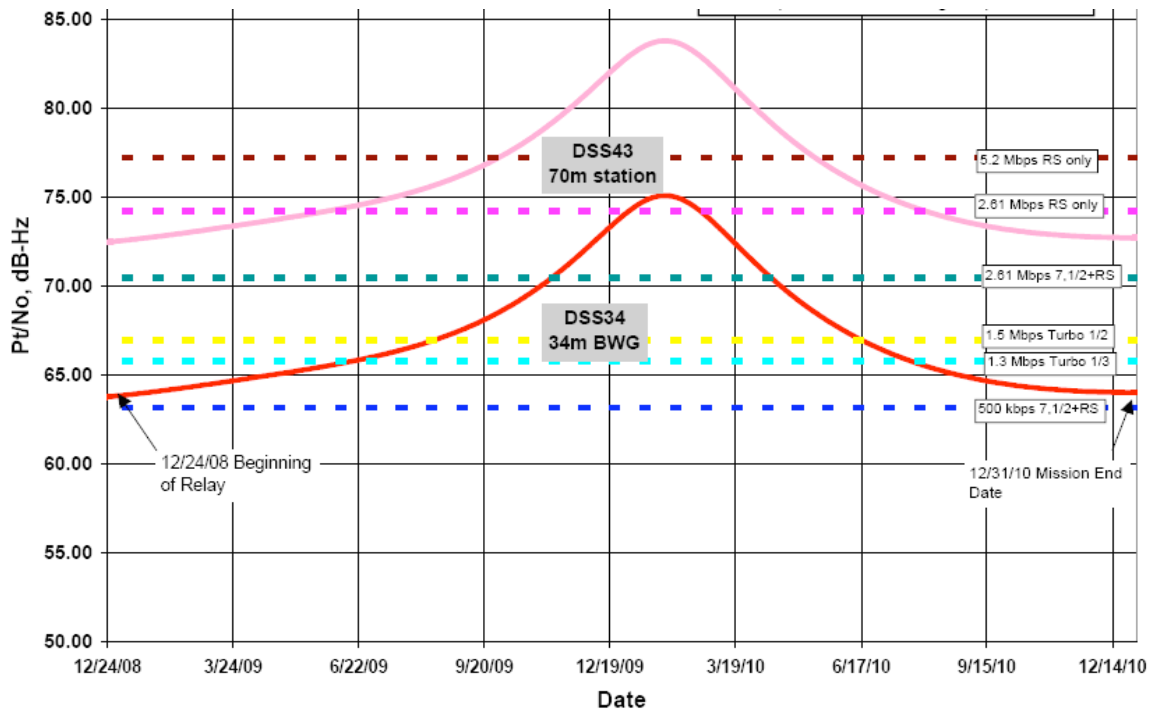

Figure 15 MRO downlink Pt/No and data rate capability

Odyssey

Uplink rates. Uplink rates range from 7.8125 bps (emergency mode via the LGA) to 1000 bps. The Odyssey project typically uses 125 bps; 1000 bps is used when necessary for large uplinks.

Downlink rates. Figure 16 shows the profile of supportable data rates at 70-m stations (red top curve) and 34-m stations (blue bottom curve) over a time span that includes several cycles of Earth-Mars distance. Proposers can extend this profile to dates of interest, as the distance repeats its 26-month cycle.

This figure is based on use of the (15,1/6) convolutional code for downlink rates between 3950 and 39816 bps. The capability of the two highest rates, 66360 and 110600 bps, is based on a (7,1/2) code.

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[3] The SDST also provides a Ka-band downlink for telemetry data. MRO defines the Ka-band link as an operational demonstration. Ka-band downlink performance will be characterized during the orbital mission using downlink rates similar to X-band.

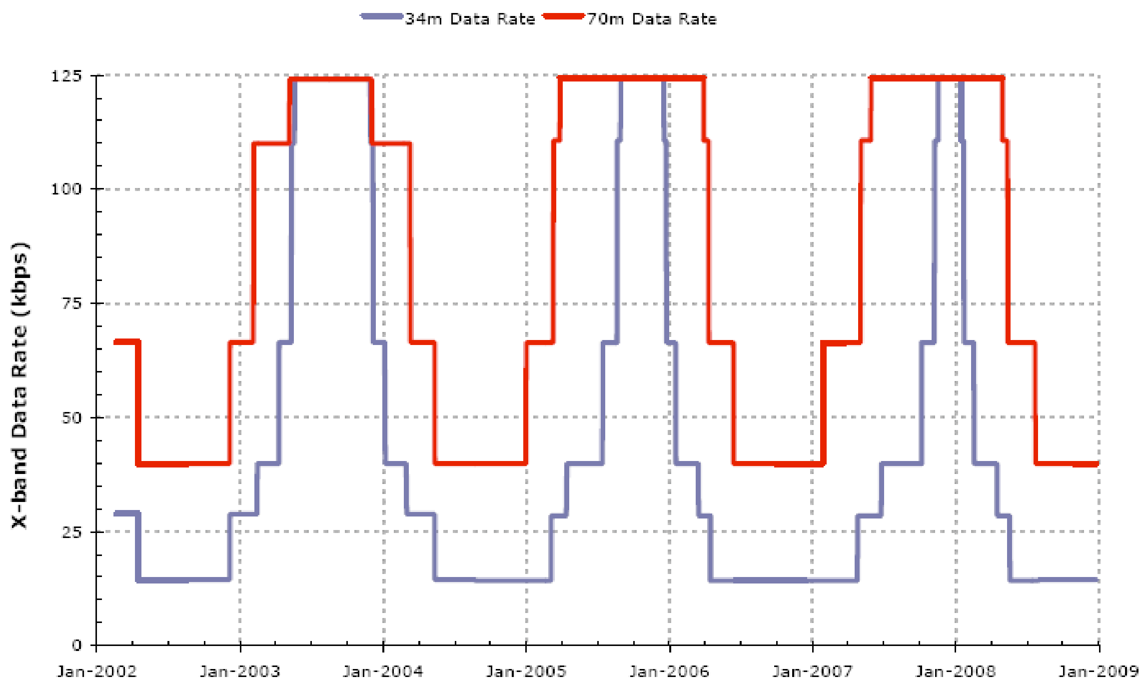

Figure 16 Odyssey supportable downlink rates to 34-m and 70-m stations

Latency

Sending data through orbiters takes more time than sending it directly to or from Earth due to the store-and-forward nature of the link. Relative to the time that a given telemetry file onboard a Scout spacecraft is ready to be sent to Earth, contributors to the end-to-end relay latency include:

- time until the next relay pass,
- relay pass duration,
- time until DSN coverage for the relay orbiter,
- potential Mars occultation of the orbiter-to-Earth link,
- time duration to transmit the relay data on the orbiter's deep space downlink,
- one-way light time between Mars and Earth
- ground processing time to deliver the data to the Scout mission's ground data system.

Similarly, for delivery of commands to a Scout spacecraft via a relay orbiter, contributions to the end-to-end latency include:

- ground processing time to deliver the command file to the relay orbiter's ground data system
- time until DSN coverage for the relay orbiter
- time to radiate the command to the relay orbiter

- potential Mars occultation of the Earth-to-orbiter link
- one-way light time between Mars and Earth
- time until the next relay contact between the orbiter and Scout spacecraft
- relay pass duration.

When DSN coverage is scheduled to overlap with relay contacts, end-to-end latencies of less than 1 hour can be achieved.

Deterministic protocols greatly enhance the ability to predict these latencies. As part of the coordination process, the orbiter project could (as Odyssey does for MER) generate weekly predictions of forward and return link latency.

EDL considerations

For critical events like Entry-Descent-Landing (EDL), MRO and Odyssey can each adjust the orbit phasing (that is, adjust the true anomaly of the orbit). However, the orbiters don't have the propellant budget necessary to make an orbit plane change (that is, significantly shift the local time of the orbit plane). Orbit phasing moves the timing of the orbiter forward or backward in its orbit so that when a spacecraft arrives at Mars, the relay orbiter will be in a good orbit position to provide telecom and navigation support for critical events surrounding arrival.

The antenna placement on an arriving/descending vehicle and that vehicle's attitudes relative to the orbiter are critical to maintain communication during EDL. It may be possible to coordinate roll steering to point MRO's antenna to cover critical EDL events.

Plasma outages may occur depending on the spacecraft's approach angle and velocity.

Compatibility Testing of User Radios

Radio to radio compatibility testing and user mission spacecraft test bed end to end information system testing are required. While each orbiter mission maintains the ground test systems necessary to support compatibility testing, the user mission is responsible for the costs of such tests.

The Scout radio (engineering model) compatibility testing may be performed against the MRO Electra GSE or the Mars Orbiter (MO) GSE which includes a CE-505 (Odyssey). The spacecraft test bench testing verifies the exact relay modes and command sequences used on both spacecraft for planned flight operations.

MER UHF pass planning and optimization

Operation of the Mars Exploration Rovers (MER) offers a rare "case study" in successful long term and the evolving use of forward and return links with orbiters.

Pass and data rate selection

Primary mission UHF pass selection was a coordinated effort involving both long-term (strategic) and short-term (tactical) planning. Strategic planning was conducted several weeks in advance by a multimission team of representatives from MER, Odyssey, and MGS. Tactical planning on a sol-by-sol basis focused on optimizing UHF data return, subject to various constraints, such as rover attitude, available energy, and expected time of data receipt on the ground. UHF relay link budgets combine with pass geometries were used to generate data volume predictions spanning a 2-week period. Results were used to identify yaw angles for parking the rover that would produce maximum average data return on the relay link. If the rover ended up significantly tilted as a result of a sol's driving, a near-term prediction run could be used to verify or update the return rate (usually 128 kbps or 256 kbps) for the next planned overflight.

MER Development and Operations Lessons Learned

UHF development

The keys to success in the UHF test program (two rovers, three kinds of orbiters, a short development schedule) included

- The full-time availability of Odyssey and MGS test sets, and MER's own UHF system test equipment (STE)
- For surface operations, choosing a few out of the many available transceiver modes and a single forward-link rate
- Insisting on testing only in the most key areas, such as measuring the extent of electromagnetic compatibility (EMC) with surface subsystems and instruments
- Knowing which equipment can be operated during UHF passes (that is, which equipment is least likely to cause interference with the UHF receiver or be interfered with by the UHF transmitter), knowledge that has proved valuable in the time- and power-constrained Martian winter
- The Proximity-1 protocol, which ensures that if data comes down at all, it's error-free data

Lesson: Ensure that similar trades are made a part of future mission implementation.

UHF link prediction

The prediction tools for forward link link margin and return link data volume worked well to help select low-elevation extra or alternative passes, significantly increasing data volume. In good areas of the rover UHF antenna pattern, the link can be closed at a 5° elevation angle. However,

- The ability to account for rover tilt in the rover-orbiter geometry was added by the end of the first extended mission. In a few cases, the expected data volume differed by a factor of 2 with and without tilt included in the prediction.
- Variability from pass to pass makes setting a margin criterion (for example, mean minus 1-sigma) challenging. It may differ for each rover as well as between the two available orbiters for a given rover.

Lesson: Projects with relay links must be capable of accurate prediction of data return commensurate with the accuracy required in sol-by-sol activity planning.

Return link latency

The MER flight team telecom analysts spent inordinate amounts of time in the primary mission answering queries about when the UHF data from each window would flow into the Mission Support Area (MSA). The mission planners required the data from one sol to plan the next sol. The on-board sequence accurately defined when the data left the rover on its way to the orbiter. However, the time the data reached the MSA varied greatly on the particular conditions on the orbiters and in the orbiters' ground systems.

After the primary mission, this situation improved somewhat when Odyssey provided a bent-pipe mode for data relay, thus defining when the first data from a UHF window would be on the ground. It improved further when the Odyssey team developed scripts for relay passes, taking into account Odyssey buffer management, to define the latest time that all data from a UHF window would be on the ground. Odyssey also developed a strategy of commanding relay attributes in near-realtime (via onboard global variables). This continues to be the mechanism by which MER requests near-term changes in return link rate, usually between 128 kbps and 256 kbps.

Lesson: All projects estimate the time each step takes when designing their operational end-to-end ground systems. The use of relay for telemetry data or for commanding adds new constraints and factors into the process.

Relay mode can return X times the data of the direct to Earth mode. Therefore, use of relay mode leaves much more time for vehicle activities other than data transmission.

Use of relay mode data or commanding, in particular commanding, puts more constraints on mission planning activities due to the orbiter relay pass timing constraints.

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3. 810-005, Rev. D, "DSMS Telecommunications Link Design Handbook", January 15, 2001, http://eis.jpl.nasa.gov/deepspace/dsndocs/810-005/